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Long-term evolution of energy and electricity demand forecasting: The case of Ethiopia

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ABSTRACT

Long-term energy demand forecasting is crucial for any country, in particular for developing countries with rapid developments of energy needs. This study focuses on Ethiopia, a country with a highly increasing energy demand resulting mainly from the currently low share of electricity access, rapid development of industrial parks, extensive expansion of the railway network, extensive irrigation schemes for agriculture, new cement and sugar factories, housing projects, power export plan to neighboring countries, etc. These all are on top of the 2.7% average population growth. In this study, the Long-range Energy Alternatives Planning System (LEAP) is used to explore different possible futures and also to forecast the long-term energy requirements in Ethiopia. The planning period is 33 years from 2018 to 2050. The study employs six different scenarios to unfold the future evolution. The developed scenarios are Business-As-Usual (BAU), Growth in Electrification and Urbanization (E&U), High Economic Growth (HEG) and three policy-driven, Improved Energy Efficiency (IEE-1, IEE-2 and IEE-3) scenarios. The pathways represented by these scenarios can show the maximum expected rise in demand under different drivers and the best-case energy saving opportunities. The model is also used to estimate the associated greenhouse gas (GHG) emissions.

1. Introduction

Long-term view spanning decades into the future is necessary to develop and manage complex policy measures that ensure investment and operational decision-making which can lead to sustainable and cost-effective ways of energy supply and demand [1]. To that end, long-term energy demand modeling is crucial in predicting the future energy utilization patterns and trends. It may contribute to strategy formulation and energy policy recommendations with respect to effective utilization of energy resources, improvements in energy efficiency and energy reliability, and emissions reductions [2].

Policymakers in both the developed and developing countries are faced with a question of how the energy sector might evolve in the future with respect to issues ranging from climate change to rural energy access. Accordingly, the use of various modelling frameworks or tools to assess how energy systems can evolve in the future is increasing. The literature provides a list of models and various approaches used to analyze energy demand, policy and planning concerns for the context of developed countries [1–9]. The most applied tools for long-term forecasting include RAMSES, BALMOREL, LEAP, WASP, MARKAL/TIMES, MESSAGE, PRIMES, HOMER, etc. Some of these approaches have been applied for investigating similar energy policy concerns in developing economies.

Developing countries differ significantly from developed countries and there are a number of characteristics, common to most developing countries, that make the modeling and forecast of their energy systems challenging [10,11]. The high reliance on traditional energies, shortages and inefficient supply in the modern sector characterized by poor performance of the power sector and limited access, rapid increase in demand for electricity and large share of rural population but rapid urbanization are some of the major challenges witnessed in developing countries. Data on prices and supply for traditional energy demand are not always available. Furthermore, the existence of multiple social and economic barriers to capital flow and technological diffusion, and frequent policy changes makes forecasting in these countries difficult [10–12]. Energy demand forecasting relies on many factors and should be able to capture the trends and relationships between the demand and independent economic, technological and demographic variables. It could be easier to perform short term forecasts through simple mathematical models. However, for the long-term forecasting, simple models

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would not be able to grasp changes and complex interactions of variables such as introduction of new technologies, energy efficient devices and government policies [13]. Additionally, future energy demand projections need to accommodate urbanization and electrification rates, environmental impacts, cost of different fuel sources and, most of all, active demand-side-management policies.

These factors should be carefully considered to understand how the energy demand might evolve in developing countries. However, there are only few studies that have attempted to examine the long-term energy use in a systematic manner within the context of developing countries [14–17]. Even though these studies employed various economic and demographic methods to develop scenarios, analyze their system and design appropriate policies; most of them constrained their scope to the electricity sector and a time span of up to 2030. Furthermore, focus is only given to future demand forecasting without considering the specific challenges faced by developing countries as mentioned in the preceding paragraphs.

In light of the mentioned, our paper focuses on Ethiopia for a number of reasons. Ethiopia is the second most populous country in Africa after Nigeria with a population of over 100 million. About eighty percent of the population resides in rural areas largely relying on traditional biomass energy resources for cooking and heating. The country has managed to achieve universal electricity access to almost all urban areas, while access to electricity in rural areas is very limited. The current access rate is 27% for rural and 96% for urban population, which translates to about 40% total access with per capita consumption of 143 kWh. Most rural customers gain access through off-grid solutions [18].

Even though, a wide range of studies with different aims examined various energy related issues of Ethiopia [19–29], only a few studies have attempted to assess the long-term energy use development [17,19, 30–32].

The Ethiopian Power System Expansion Master Plan [30], completed in 2014, was done for Ethiopian Electric Power (EEP) for the period 2013–2037. It uses a macroeconomic multi-variable regression analysis load forecast model and end-user models to determine a 25-year least cost generation and transmission system development plan. Recently, a new update of the master plan was developed [31]. It uses regression analysis models and bottom-up sales by considering scenarios (low, base-case and high-growth) and sensitivity forecasts. The Ethiopian energy economy report projected the energy demand from 2008 to 2030 by the Ethiopian Economic Policy Research Institute [32]. The report projects the demand using energy demand coefficients and macro-economic variables.

The above studies [30–32] aim to forecast the future energy demand; however, it is important to provide a way of exploring different possible futures that can be meaningful for policy development. In this regard, there are only a few studies that applied energy demand scenario analysis for Ethiopia [19]. considers business as usual (BAU), moderate shift and advanced shift scenarios of economic development over the period of 2010–2050 to assess sustainable energy system strategies including energy demand projections [17]. forecasted sector-wise energy demand up to 2030 by developing three alternative scenarios on improved cookstoves, efficient lighting, and universal electrification. The results mainly suggest that alternative investments can conserve energy and improve environmental sustainability of the country. Even though these two studies attempted to explore the future demand, the developed scenarios did not fully consider the rate-of-change in socio-economy, technological change and future governmental direction.

Considering the identified literature gaps, this paper aims at seeking answers to these questions:

- What are adequate approaches to capture the specific features of modeling energy demand of developing countries?
- What are the forecasts for the Ethiopian demand and its various sectors, total energy utilization and electricity consumption under different scenarios?
- What is the effect of introducing energy efficiency policies in terms of economic, social and environmental contexts of the country?

The structure of the article is as follows. In Section 2 we provide an overview about Ethiopia, its energy sector and electricity demand trends. Section 3 discusses the research methodology and approaches followed. Section 4 describes the model, data and scenarios in detail. Section 5 presents the main findings of our study with its analysis. Finally, Section 6 discusses the main conclusions and policy implications of the study.

2. Country overview

2.1. Overview of the energy sector in Ethiopia

Over the past decade, Ethiopia has been one of the fastest growing economies in the world with annual rate of economic growth averaging 10.3% over the 2005/06–2015/16 period [33]. The country has a vision of becoming a lower-middle-income country by 2025 after implementing three successive five-year development plans referred to as the Growth and Transformation Plan (GTP). The main objective is to eradicate poverty in a relatively short period of time by implementing broad-based development policies to enhance growth [34,35]. This development is translating into a large demand for energy in urban and rural areas.

The highest increase in demand for energy is envisaged to come from developing countries where, growing population, rapid urbanization, rise in living standard and income are prevailing [36]. In this regard, Ethiopia can be taken as the best example and representative for studying the context and characterization of the energy system in developing countries. Moreover, most of the challenges mentioned in the introduction are faced by the country.

The primary source of energy in Ethiopia is biomass, which accounts for 91% of energy consumed, petroleum supplies about 7% and electricity only 2% of total energy use [17,37]. In about 95% of Ethiopian households, cooking is done with polluting fuels and technologies and the proportion is almost 100% in rural areas [38]. Different studies [17, 25,27,37–39] show that the national energy balance is dominated by a heavy reliance on firewood, crop residues and dung.

Ethiopia has a high potential for solar, wind and hydropower in addition to geothermal and bioenergy. However, the country's renewable energy potential is largely untapped. The power generation is dominated by hydropower accounting for some 90% of the total. The interconnected system (ICS) consists of 13 hydro, six diesel standbys, one geothermal and three wind farm plants with installed capacities of 3814 MW, 87 MW, 7.5 MW and 324 MW, respectively. This amounts to a total of 4233 MW [40].

Currently, Ethiopia is facing a serious energy shortage enforcing electricity load shedding in all consumer categories. Electricity shortage is prevailing due to lags in power plant construction and increase in demand [23].

2.2. Electricity demand trends

The country's historical electricity consumption is presented by grouping customers in representative categories such as domestic, low-voltage (LV) industrial, high-voltage (HV) industrial, public and regional export. All customer groups are connected to the distribution system except the high-voltage industrial customers which are connected to the transmission system. Complete data is available since 2001 with total electricity consumption of 1388 GWh and it is raised to 10,750 GWh in 2017 with an average growth rate of 13%. The historical consumption distribution by the different customer groups is shown in

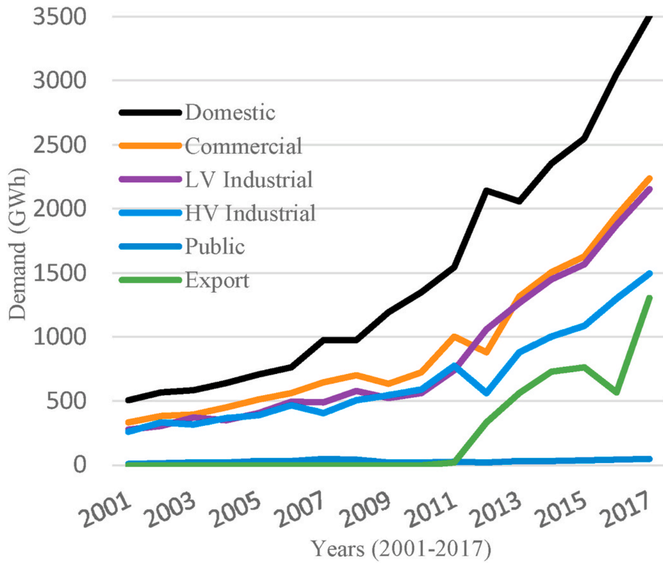

Fig. 1. Historical electrical energy demand trends in various sectors of Ethiopia [31].

Fig. 1.

For the considered 17 years, the industrial sector (HV&LV) consumed 36% of the total, the domestic sector 35%, and the commercial sector 22%. The remaining 7% is export to neighboring countries (Djibouti and Sudan) and public loads such as street lighting. The total electricity consumption in the domestic sector was 508 GWh in 2001 and raised to 3509 GWh in 2017. Such significant rise in domestic power demand in developing countries has been more prominent in contrast to industrialized nations due to the high rate of urbanization, growth in population and wealth [41,42]. It is essential to consider these factors when dealing with modeling and electricity demand forecasting of a country like Ethiopia.

3. Methodological approach

Scenarios support the early detection of emerging issues and help policymakers prepare for otherwise surprising developments [43]. Accordingly, the energy demand projection is done with two alternative and three policy-driven scenarios in addition to the "business-*as*-usual" reference scenario.

The development and selection of appropriate scenarios is one of the major considerations in representing the characteristics of the energy systems in developing countries. Failure to represent the features and factors that influence the energy system poses the risk of producing inaccurate results and thereby recommending wrong policies. Accordingly, the scenarios are developed by studying the country's context in terms of energy demand, socio-economy, demography, technological change and future governmental direction in a systematic manner.

The energy demand projection is done for different sectors. Specifically, the electricity demand forecasting is done for various customer categories connected at different stages of the power grid (i.e. different voltage levels). They are categorized as household (HHE_t), HV industry ($HVIE_t$), LV industry ($LVIE_t$), commercial (CME_t), agriculture (AGE_t), transport (TRE_t), public (PBE_t) and export ($EXPE_t$). A demand forecast is made for each of the categories. Then, the total country demand forecast (TED_t) is taken by adding each of the forecasts as shown in equation (1).

$$TED_t = HHE_t + HVIE_t + LVIE_t + CME_t + AGE_t + TRE_t + PBE_t + EXPE_t \tag{1}$$

Total losses (EL_t) are calculated based on governmental loss reduction targets (TL_t) that is added to the total demand (TED_t).

$$FTED_t = TED_t + EL_t \tag{2}$$

and

$$EL_t = \left(\frac{TL_t}{1 - TL_t}\right) \cdot TED_t \tag{3}$$

where EL_t refers to the total transmission and distribution (T&D) losses in year t, TL_t is the T&D losses in terms of percentage of total generation in year t and $FTED_t$ is the final total electricity demand in year t.

The employed demand forecast method is a combination of bottom-up approach and multi-variable regression modeling. Bottom-up consumer level sales forecast is applied to selected customer groups with explicit government plans for new connections and expansions of various projects. In addition, customer applications to the utility company for future supplies and connections to their premises are also included. Such customer groups demand a huge amount of electricity and are usually connected to the transmission system. These customer groups include industrial parks, railway expansion projects, Addis Ababa light-rail project, sugar industry, cement industry, irrigation, steel and metal industry, mining and regional power export.

On the other hand, we used a multi-variable linear least-square regression modeling for the other sectors such as general HV industry, LV industry, commercial, public and fuel transportation.

$$D_t = B_0 + B_1 \cdot X_{1t} + B_2 \cdot X_{2t} + \cdots + B_n \cdot X_{nt} + B_{n+1} \cdot D_{t-1} \tag{4}$$

where D_t - the dependent variable, is the energy demand in the year t, and D_{t-1} is the energy demand in the previous year t-1; $B_0, B_1, .., B_{n+1}$ are the regression weights that are computed in a way that minimize the sum of squared deviations; $X_{1t}, X_{2t}, \ldots X_{nt}$ are the independent variables that potentially impact demand in the specific customer group. These are selected from the entire list of variables such as historical consumption, GDP, per capita income, number of customers and number of households.

4. Model, data and scenarios

Long-range Energy Alternatives Planning System (LEAP) model is a widely used software tool for energy policy analysis and climate change mitigation assessment. It is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. The model follows the accounting framework approach to generate a consistent view of energy demand based on the physical description of the energy system. Studies using LEAP are diverse in terms of geographical scale, sectoral coverage, and focus of study. This software has been exploited to investigate electricity sector and energy sector of several countries [16,44–48]. In particular, it is a widely used tool for energy demand prediction and scenario analysis in developing economies [14,15,17].

Future energy demand in developing countries is highly dependent on the economic and social contexts in addition to new technological innovations. However, these are subject to large uncertainties that are difficult to predict. Therefore, the exploration should be based on scenario-analysis that can be drawn by studying the country's socio-economic context that gives an understanding of the high uncertainties of the future energy demand. In addition, sector wise and technological representation of end-uses at a disaggregated level is highly required. This includes the rural-urban divide, economic and/or technological transitions, the informal sector and supply shortage features. In this regard, LEAP is an appropriate modeling tool for making energy analysis and the current study, as other studies, utilizes this tool to explore and forecast the energy demand up to the year 2050.

4.1. Model

The energy demand model is primarily structured sector-wise, namely: residential, industrial, commercial, agriculture and transport sector. The data structure for the residential sector follows a bottom-up approach, by using end-use device accounting techniques in LEAP-standard. The residential sector is divided into two main subsectors. i.e. urban and rural. Another division, electrified and non-electrified is also created as shown in the demand model tree in Fig. 2. It contains four end-use categories including lighting, cooking & baking, refrigeration and other devices (TV, radio, computer, iron, etc.). Data inputs such as population, number and share of households are given to the activity level variable whereas energy consumption data is entered to the final energy intensity variable. The data structure for the remaining sectors is done based on common energy use in different applications or end-uses.

4.2. Data and key assumptions

4.2.1. Key assumptions

Data used in this study is based on extensive data collection, mainly from the electric power sector, including the Ministry of Water, Irrigation and Electricity (MoWIE), Ethiopian Energy Authority (EEA), Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU) and National Load Dispatch Center (NLDC) but also from other sectors: Central Statistics Agency of Ethiopia (CSAE), National Bank of Ethiopia (NBE), National Planning Commission (NPC) and Ethiopian Petroleum Supply Enterprise (EPSE). In addition, necessary local [18,35,37,42,49] and international reports are also used as data sources [33,34,38,50].

LEAP has four different modules for data input: key assumptions, demand, transformation and resources. Key assumptions include various socio-economic variables such as country population, urban and rural population, households, GDP and other similar data which affect the level of final energy consumption. The demand module contains the various sectors and customer categories which consume energy such as household, industry, commercial, public and others. In the transformation module, the process of converting primary energy into secondary energy is done and data such as conversion losses are given. Lastly, the resource category includes data for the supply/resource technologies.

In this study, the demand module is sub-categorized into domestic, HV industry, LV Industry, Commercial, Agriculture, Transport, Public and Export. In the transformation module, energy loss data of the power system is given. The demand projection is done for 33 years up to the year 2050 considering 2018 as the first simulation year.

4.2.2. Appliance activity level and energy intensity

The demand data for the domestic sector is entered according to the LEAP demand tree shown in Fig. 2. Accordingly, the major end-use or appliance categories are divided into lighting, cooking & baking, refrigerator and other-uses. These appliances have different level of penetration and energy consumption in an average household.

It can be seen that in 2017, 94% of urban households and only 11.7% of the rural households had access to basic electricity. The remaining 6% of urban and 88.3% of rural households had no access to any electricity source and relied on alternative sources mainly kerosene for lighting and wood, charcoal and liquefied petroleum gas (LPG) for cooking and baking.

In addition, to cope with insufficient hours of service and power outages, households use backup solutions for lighting such as candles, torches/flashlights and kerosene lamps. Urban households rely heavily on candles as a back-up solution, while rural households rely more on dry-cell batteries and kerosene lamps. 4.8% of urban households and 25.8% of rural households use kerosene as a back-up solution [51].

In Ethiopia, 63.3% of households use a three-stone stove as their primary stove, 13.6% use a self-built stove as their primary cooking solution, 18.2% use a manufactured biomass stove, and 4.2% use a clean fuel stove with electricity and LPG. Less than 1% of households use LPG as their primary cooking solution, while 96% of the households use biomass fuels [38,51]. A three-stone stove is a pot balanced on three stones over an open fire. A self-built stove is typically an enclosed stove made using stone, mud, and flat clay that can be slightly more efficient than a three-stone stove. A manufactured biomass stove is typically produced in a factory or by an artisan and usually made of metal and can be considered an improved cookstove. Ethiopian households commonly use injera (traditional Ethiopian bread) and bread baking stoves in addition to regular stoves for cooking (making sauce, tea, coffee, etc.) which consumes between 40% and 65% of the entire household cooking fuel consumption [52].

Urban and rural households use different cooking technologies: 54.3% of urban households use a manufactured stove and 15.3% use a clean fuel stove, while 77% of rural households use a three-stone stove. And 85.4% of rural households use firewood as their primary fuel, while 60.3% of urban households use charcoal [51]. Most households in both urban and rural areas use multiple stove types (i.e. different combination of three-stone stove, self-built, manufactured and clean stove).

According to Ref. [51], five different capacity tiers are used to

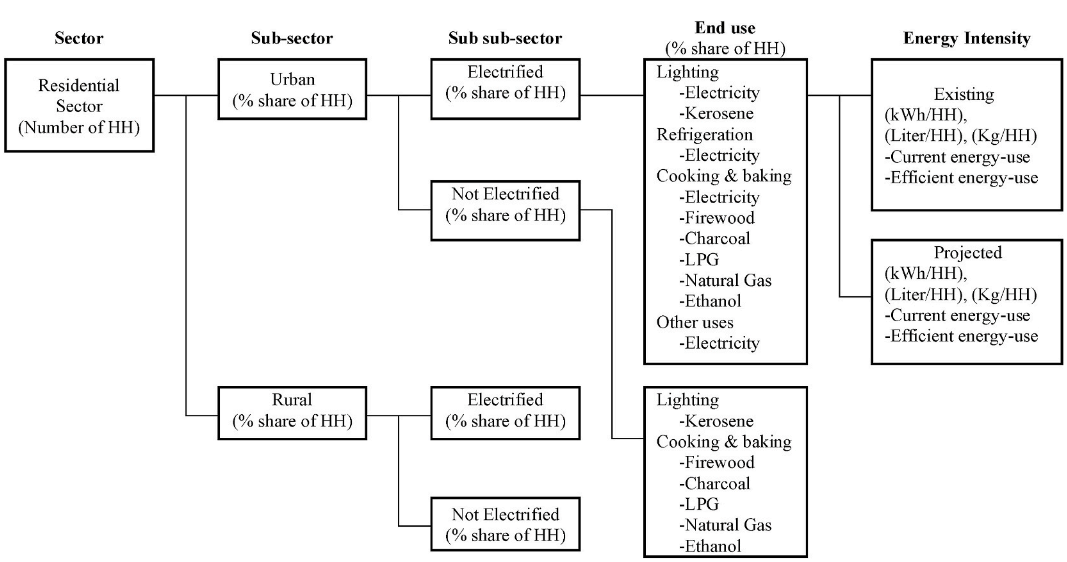

Fig. 2. The developed LEAP energy demand tree for the residential sector of Ethiopia.

classify the penetration of appliances in urban and rural areas. Medium-load appliances such as refrigerators, freezers and air coolers are assigned in TIER 3 with penetration of 50.5% urban and 5.7% rural grid-connected households. Other-use electrical loads include television, radio, computer, phone charging, etc. Are under TIER 1 and 2 which account a penetration of 61.1% in urban households and 75.3% in rural households.

The energy intensity of cooking stoves depends on the cooking technology, fuel type and amount of consumption. In terms of thermal stove efficiency, electric and ethanol stoves have the highest efficiency of about 60%, followed by LPG (55%), kerosene (42%), charcoal (25%) and firewood (10%) [53]. Among the firewood stoves, the manufactured-type has a better efficiency than the self-built and three-stone types. In a study conducted in the field, the fuel saved by the manufactured-type was 22–31% of that with a three-stone fire [54].

Accordingly, by making simple calculations based on daily consumptions, assuming 30% fuel reduction from manufactured-biomass stoves and 10% reduction from self-built stoves; the energy intensity for the different stoves is determined. Energy intensity for injera/bread baking stove is assumed to be 65% of the total fuel cooking consumption (1057 kg per person) [52].

Table 1 shows the penetration and energy intensity of the electrical appliances applied in LEAP for both urban and rural households. Lighting utilizes 30% of total urban and 42% rural electricity consumption which is calculated to be about 503 kWh and 235 kWh per year per household respectively. Cooking utilizes 35% and 19% of the total consumption. The remaining is consumed by refrigerator and other-use loads. Lighting is assumed to be fully penetrated device as both urban and rural households solely depend on electrical lamps for lighting. Whereas the remaining appliances have partial penetration with electrical stoves accounting only 15.3% urban and 0.6% rural households. The total electricity consumption per household in 2017, is 1676 KWh for urban households and 559 kWh for rural households which is approximately one-third of the urban.

4.3. Scenarios

In this study, we employ six different scenarios for the projection of the future energy demand. One is a business-*as*-usual (BAU) scenario or reference scenario which assumes continuation of current policies, programs and targets of the government, two scenarios are alternative scenarios reflecting the uncertainty about future development and the remaining three are policy scenarios. The two alternative scenarios are based on the reference scenario (inherit BAU properties) but with different rate-of-changes of some particular activities such as socio-economy, demography, technological change and future government direction. The three policy scenarios are policy-driven scenarios that are

Table 1
Electrical appliance penetration and average energy intensity for electrified urban and rural households in 2017.

Appliances	Activity Level (% saturation)	Energy Intensity (kWh/HH)
Urban		
Lighting	100	503
Cooking	15.3	587
Refrigerator	50.5	453
Other uses	61.1	133
Total electricity consumption		1676
Rural		
Lighting	100	235
Cooking	0.6	106
Refrigerator	5.7	168
Other uses	75.3	50
Total electricity consumption		559

applied to each of the other scenarios (reference and two alternative scenarios). In the scenarios, population, urbanization, GDP, electrification and other socio-economic factors are set to change. In addition, efficiency improvements from technological advances and demand side management programs are considered to be the main factors for reduction in energy demand over time.

Hence, scenarios of growth in electrification and urbanization (E&U), high economic growth (HEG) and improved energy efficiency (IEE) are designed and their results are mainly compared with the BAU scenario to understand possible deviations from the normal demand forecast. In addition, their impact on GHG emissions is also assessed. We employ the LEAP scenario manager to create and then evaluate the alternative scenarios by comparing their energy requirements and environmental impacts. This enables us to see how the energy demand might evolve over time. Below we provide the input data, assumptions and methods used in the reference, alternative and policy scenarios for making the energy demand forecasting.

4.3.1. Business as usual (BAU) scenario

The BAU/reference scenario is the base of all other scenarios and assumes that historical trends will continue into the future by giving special attention to government policies and strategies. Historical trends of population growth, GDP growth, electrification, urbanization and consumption of energy by sector are used to project the future demand. In the BAU scenario, it is assumed that the country has no ambition to reduce CO_2 emission and no endeavor to shift to clean fuels. In addition, it is assumed that the current power shortages and interruptions will continue in the future and back-up solutions are necessary. Biofuels such as ethanol and LPG are considered as an important fuel for the last two decades. The energy intensity of electric stoves is assumed to increase by 50% in the year 2040.

The Central Statistics Agency of Ethiopia has forecasted the population and urbanization levels until the year 2037 [42] and these levels are used in the BAU scenario. For the remaining years from 2038 up to 2050, the historical trend has been projected with 1.6% (2038–2042) and 1.4% (2043–2050) population growth rates. Similarly, the urbanization level is targeted to increase from 31.1% in 2037 to 60% in 2050.

In 2017, the government of Ethiopia (GoE) introduced an ambitious program, the National Electrification Program which aims to achieve universal access to electricity nationwide by 2025 [55]. According to this plan, 65% of households are expected to be supplied through grid-connection and the remaining 35% via off-grid technologies by the end of 2025. Then, by 2030; grid expansion will reach out to 96% of households and only 4% will be supplied via off-grid systems. Accordingly, the BAU scenario is based on this target. However, the progress made in the last two years since the program's launch is slower (40%) compared to the target set (47% total access by 2019). Therefore, considering a similar electrification pace, we have only applied the grid-access target (i.e. 65% by 2025 and 96% by 2030) by neglecting the off-grid access target.

Future GDP growth rate assumptions are based on historical trends, considering IMF predictions and our judgement. Total GDP growth rates of 9%, 7% and 4% are assumed for the years until 2030, 2040 and 2050 respectively. The per capita income growth rate is assumed to be 9% (2018–2030), 7% (2031–2040) and 5% (2041–2050). The reduced growth rate used for later years is associated due to creating a mature and larger economy. Customer growth rate assumptions also depend on historical trends while considering the roles of population growth and grid expansion targets. Customer growth rates of 8%, 6% and 5% for commercial and LV industry, 12%, 8% and 6% for HV industry and 6%,4% and 3% for public load is assumed for the years until 2030, 2040 and 2050 respectively. The summary of all the assumed growth-rates and projected values for the macroeconomic, demographic and other variables for all the scenarios is shown in Table 2.

Electricity demand projections are made for 17 industrial parks which recently have become operational, are under construction, or

Table 2
Assumptions of growth-rates and projected values for different variables under each scenario.

Index		[a]Pop'n growth rate	HH size	[b]Urban'n	Urban [c]electr'n	Rural electr'n	Total GDP growth	Per capita income growth	Electric stove [d]pen'n		[e]Total loss
Unit		%	People per HH	%	%	%	%	%	% of urban HH	% of rural HH	%
2020	BAU	2.1	4.7	21.8	96.3	38.0	9.0	9.0	17.1	4.1	21.1
	HEG	2.1	4.7	21.8	96.3	38.0	**11.0**	**11.0**	17.1	4.1	21.1
	E&U	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	21.1
	IEE	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	**21.3**
2030	BAU	2.0	4.7	27.1	100	96	9.0	9.0	30.0	15.0	17.3
	HEG	2.0	4.7	27.1	100	96	**11.0**	**11.0**	30.0	15.0	17.3
	E&U	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	17.3
	IEE	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	**12.5**
2040	BAU	1.6	4.6	37.8	100	100	7.0	7.0	35.0	30.0	12.5
	HEG	1.6	4.6	37.8	100	100	**8.0**	**9.0**	35.0	30.0	12.5
	E&U	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	12.5
	IEE	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	**9.0**
2050	BAU	1.4	4.6	60.0	100	100	4.0	5.0	40.0	40.0	12.5
	HEG	1.4	4.6	60.0	100	100	**6.0**	**6.0**	40.0	40.0	12.5
	E&U	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	12.5
	IEE	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	**9.0**

The bold numbers indicate that the value specified for the given scenario is different compared with the assumption in the BAU scenario.
[a] Population.
[b] Urbanization.
[c] Electrification.
[d] Penetration.
[e] Total power system loss.

planned to be developed in the long-run. Feasible operating periods and demand levels at different years are assumed considering the location, construction time and investment opportunity. In addition, future unidentified industrial parks are also included in the projection. These are expected to be operational from 2030 up to 2050 with increasing consumption.

Considering customer electricity supply requests brought to the utility from cement, mining, steel and metal industries, the energy demand is projected for the future years. A similar approach is followed for the agriculture, transport and export sectors. In the transport sector, the cross-country railway lines of Ethio-Djibouti, Addis Ababa light railway and 10 other national railways connecting.

different cities are considered. Reasonable future expansions are assumed for each of the projects. Increased export of electric power and natural gas to neighboring countries is considered. Electric power export to Sudan and Djibouti has already been started in 2017 with 1.5 TWh and is set to reach 35.3 TWh by 2045. Export of natural gas will start in 2021 with 10 million metric cube and is assumed to increase up to 50 million metric cube and 500 million metric cube by 2030 and 2050 respectively.

A rapid rise of demand for solid fossils is assumed in industry, particularly for cement and steel & metal industries. Complete reliance on fossil-fuel consumption is also assumed in the transport sector which is expected to produce significant growth of diesel, gasoline and jet fuel demands. The projection is done using regression modeling based on the variables total GDP, service GDP and previous year demand. Increased use of petroleum is also assumed in the agriculture sector for irrigation and other farm activities. Petroleum use in the agriculture and LV industry is set to grow at 9% annual growth rate.

Power loss assumptions are based on reduction targets and by reviewing the progress made in the past few years. The total loss target is assumed to be continuously reducing from the average historical loss of 23%–12.5% by 2040 through implementing projects of network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc.

4.3.2. High economic growth (HEG) scenario

As mentioned in the introduction, Ethiopia has a big vision of attaining lower-middle-income country status by 2025 after implementing successive development plans. This has led to remarkable achievements in real GDP growth, infrastructure development and social development which translates into a large demand for energy. The HEG scenario builds up on the BAU/reference scenario by assuming the continuation of high economic growth in the country. Total GDP growth of 11%, 8% and 6% is considered for the years until 2030, 2040 and 2050 respectively. The GDP growth by industry is assumed to be 11%, 8% and 5% while the service sector is expected to grow by 10%, 8% and 6%. The agriculture sector GDP growth rate is assumed to be the same as in the BAU scenario (i.e. 9%, 8% and 5%). Finally, the per capita income growth rate is targeted to hit 11%, 9% and 6% for the future three decades.

4.3.3. Growth in electrification and urbanization (E&U) scenario

The E&U scenario is also based on the BAU scenario but with major differences in country policy and direction. It is assumed that the country has a strong ambition to reduce CO_2 emissions through various initiatives. One of these initiatives is to push for a rapid-shift from biomass-based household consumption to clean-fuel based consumption. Biomass-based cooking and injera/bread baking stoves are assumed to significantly reduce their penetration over time. Firewood cooking and baking stoves are targeted to be used in less than 10% and 40%, respectively, of households by 2045. Instead, electric stoves are expected to penetrate 65% of urban households by 2035 and 70% of rural households by 2045. With such a shift to electric stoves and the future additional new demand, the energy intensity is expected to double by 2040. In addition, biofuel-based and natural gas-based cooking stoves are targeted to penetrate 30% of households.

The scenario targets 100% electrification by the end of 2025. In order to reduce the transport sector CO_2 emissions, electric vehicles are assumed to be deployed in 2025 with increasing penetration for later years. 1.1 million electric cars are set to replace fossil-fuel based cars by 2050.

Historically, Ethiopia had a low level of urbanization. However, since 2007, government policies helped the growth of small towns and infrastructure development which increased the tempo of urbanization. In addition, implementation of the GTP with objectives of increasing employment generation in urban areas is likely to result in higher rural to urban migration and thus faster urbanization [42]. Accordingly, this scenario assumes a faster-urbanization rate of 6% per year resulting in

80% urban population by the year 2050.

4.3.4. Improved energy efficiency (IEE) scenario

Ethiopia has significant transmission and distribution bottlenecks that limit the delivery of the existing supply from reaching demand centers. Poor reliability, significant transmission and distribution (T&D) losses and low power quality affect the end-use consumers. These capacity, reliability and quality constraints compromise the ability of the electricity sector to support sustained economic growth. Realizing this, the GoE is actively exploring how demand-side management (DSM), energy efficiency and conservation can help lower cost and improve economic growth [56]. Accordingly, principal energy efficiency and conservation programs and projects are underway. Some of these include standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. In the standards and labeling program, minimum energy performance standards are to be developed for the main industrial loads and household appliances. These include electric motors, injera cookers, electric cookers, lighting, refrigerators and freezers, etc.

Therefore, this scenario is a policy-driven scenario that explores the long-term demand evolution by assuming significant efficiency improvements in the electricity sector. The efficiency improvements are applied to each scenario; i.e. the BAU (IEE-1), HEG (IEE-2) and E&U (IEE-3).

Introducing industrial energy audits and industrial efficiency measures on the use of electricity can have the potential to save up to 30% of the electricity consumed in the industry sector by 2040. As a result, progressive efficiency gains are assumed to be effective in the LV industry and HV industry (excluding industrial parks) from the base year until 2040.

Improved lighting standards and DSM programs are expected to reduce the energy intensity of electric lighting in urban households by 1% every year starting from the base year. Similarly, electric stove energy intensity reductions are expected to achieve 0.5% per year. The other assumption is on energy efficiency improvement of refrigerators in urban households with energy intensity reduction of 5% in 2020 and 20% in 2040.

A program to install efficient street lighting systems could also reduce electricity consumed in the public sector. The use of efficient light emitting diodes (LEDs) with proper controlling and monitoring system can reduce the electricity consumption by 60% compared to the conventional street lighting system. The program is assumed to start in 2018 and by the end of 2030 all streetlights in the country are expected to meet the new requirement.

Regarding T&D losses, the government is expected to implement network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc. that result in power quality and system efficiency improvements. Accordingly, the total power loss is targeted to reduce to 12.5% by 2030 and to 9% by 2035.

5. Result and analysis

5.1. Demand projection

The final energy demand, fuel consumption and GHG emissions are derived for each of the scenarios and end-use categories. The projected demand for the BAU scenario is about 2950 PJ by 2030 and 4900 PJ by 2050, a growth of 90% and 215% compared to the demand in the year 2017. Fig. 3 shows the projected energy demand by sector. The domestic sector has the highest share with 2273 PJ in 2030 and 2844 PJ in 2050 accounting for 77% and 58% of the total demand respectively. It displays a sharp increase until 2040 and remains at a saturation level afterwards. The transport sector is the second major energy demanding sector, showing a significant increase in the last two decades. It accounts for 25% of the total energy demand in 2050. The HV industry, LV industry and other sectors are expected to gradually increase their demand over time.

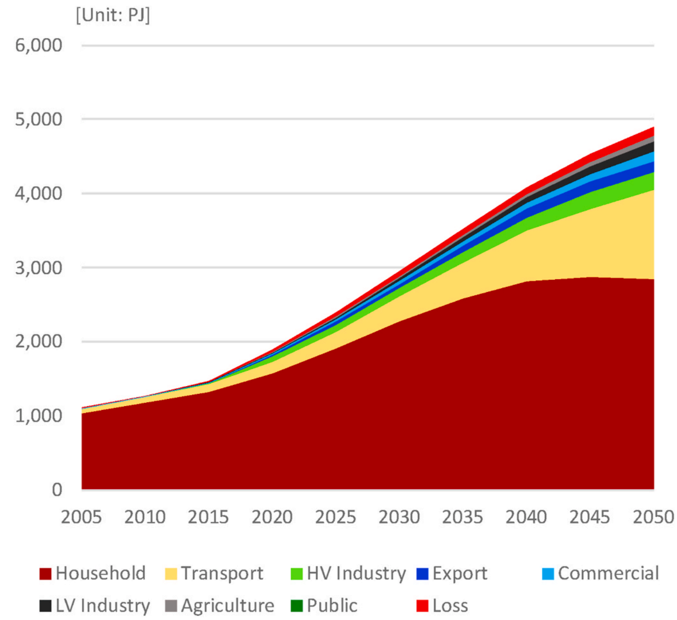

Fig. 3. Final energy demand under BAU.

5.2. Comparison of demand under various scenarios

A comparison of the scenarios shows that the energy demand is highest for the HEG & IEE-2 scenarios followed by the BAU & IEE-1 and E&U & IEE-3 scenarios (see Fig. 4). There is a huge difference between E&U vs. BAU and IEE-3 vs. BAU. The HEG scenario is based on the BAU scenario but assumes a higher economic growth-rate which incurs additional energy demand. The final demand is expected to reach about 5255 PJ by 2050. Assumption of total GDP growth rates of 11%, 8% and 6% for the future three decades results in demand increase by 7% compared to the BAU scenario in 2050. On the other hand, the energy demand reduces by 42% in E&U scenario and by 46% in IEE-3 scenario.

In the case of electricity demand, the result shows that the highest

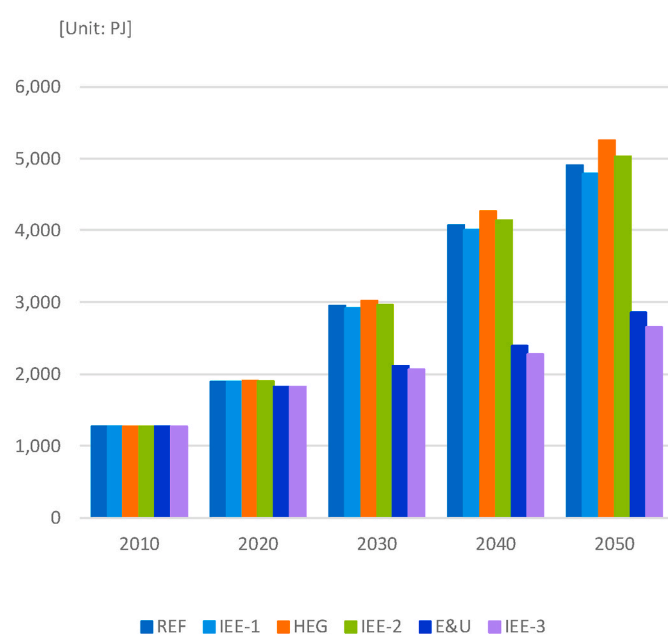

Fig. 4. Total energy demand for all scenarios.

demand is expected for the E&U scenario since more electricity-based end-uses are utilized (Fig. 5). In 2050, the total electricity demand under the E&U scenario is expected to reach 292 TWh while HEG demands 289 TWh and BAU consumes 262 TWh. The total energy saving under the IEE scenarios is estimated to be about 43 TWh (IEE-1), 63 TWh (IEE-2) and 56 TWh (IEE-3) in 2050. Technology improvement and DSM activities account 28%, 19% and 41% of the energy saving in IEE-1, IEE-2 and IEE-3, respectively. Industrial energy audit and efficiency measures contribute to 41% (IEE-1), 55% (IEE-2) and 31% (IEE-3) of the total savings while network loss reduction contribute to 30%, 25% and 27%, respectively. The remaining 0.5–1% is due to technology improvement in streetlights.

Fig. 6 shows sector-wise electricity demand projections under the policy-driven scenarios (IEE-1, IEE-2 & IEE-3). It can be seen that the household sector demand is strongly increasing and in 2050 the household sector is anticipated to consume about 23%, 22% & 25% of the total electricity demand in IEE-1, IEE-2 and IEE-3, respectively.

IEE-2 does not have much effect on the household consumption share compared to HEG (i.e. both 22%) while IEE-1 & IEE-3 reduce the share by 1% & 3% compared to BAU (24%) & E&U (28%), respectively. This implies that the policy-driven measures applied to E&U scenario (IEE-3) have stronger impact on household consumption compared to the others (IEE-1 & IEE-2).

5.3. Fuel consumption

The fuel consumption is dominated by wood, accounting for 73% of the total fuel consumption by 2030 and 51% by 2050 (Fig. 7). This is mainly due to the household fuel consumption (Fig. 8) where 94% of total fuel consumption in 2030 (88% rural and 12% urban) and 86% in 2050 (66% rural and 34% urban) is from wood. Our analysis also shows that the use of traditional biomass will continue increasing until 2040 under the BAU and HEG scenarios. On the contrary, for the E&U & IEE-3 scenarios, biomass use is expected to reach its peak in 2022 and then decline from 2023. From Fig. 7, it can be seen that the electricity demand is expected to increase drastically from 107 TWh (13% of total fuel consumption) in 2030 to 262 TWh (19% of total fuel consumption) in 2050. Fossil fuels like diesel, gasoline and jet kerosene will also see an increasing consumption due to expansion of fossil-fuel-based road transportation and aviation.

Fig. 8 shows that the household fuel consumption in the E&U scenario is entirely different from the BAU & HEG scenarios. In 2050, the total fuel consumption in E&U is more than 65% lower than in the other two scenarios. In addition, in E&U, the penetration of electricity increases strongly, to 30% of the total fuel consumption while wood share is about 55%.

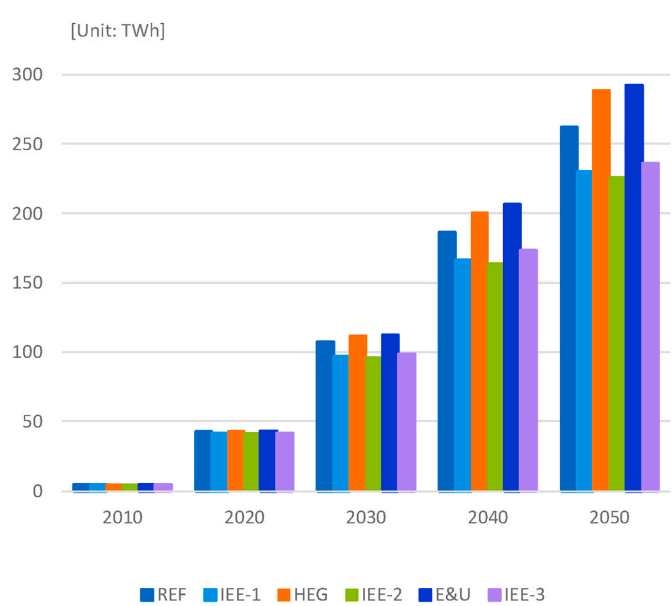

Fig. 5. Electricity demand for all scenarios.

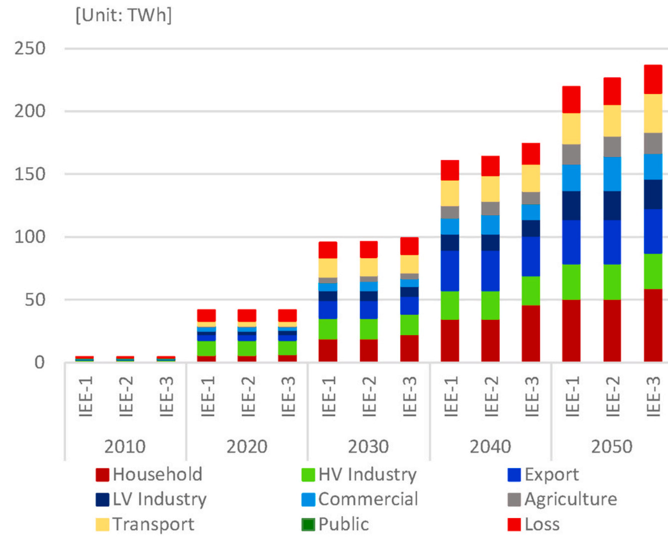

Fig. 6. Electricity demand under policy-driven scenarios.

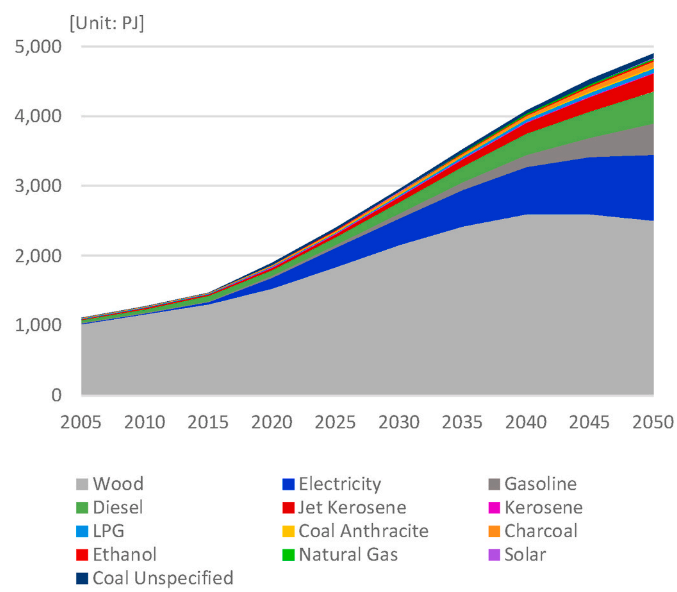

Fig. 7. BAU fuel consumption.

5.4. Greenhouse gas emissions

It is observed that under the BAU scenario in 2030, biogenic carbon dioxide emissions reach 122 million-ton CO_2e, 30 million-ton non-biogenic CO_2e and about 11 million-ton non-CO_2 (Fig. 9 and Fig. 10). Biogenic carbon dioxide emissions are defined as emissions from a stationary source directly resulting from the combustion of biologically based materials, mainly from biomass burning while non-biogenic CO_2 emissions are from the use of transportation fossil-fuels. In this study, biogenic CO_2 emissions are not treated as “carbon neutral” despite the fact that the country is taking various initiatives to tackle deforestation by planting many trees. Regrowth is not sufficient and the large amount of carbon released into the atmosphere due to burning of biomass may take decades for new forests to absorb. This shows that the process has

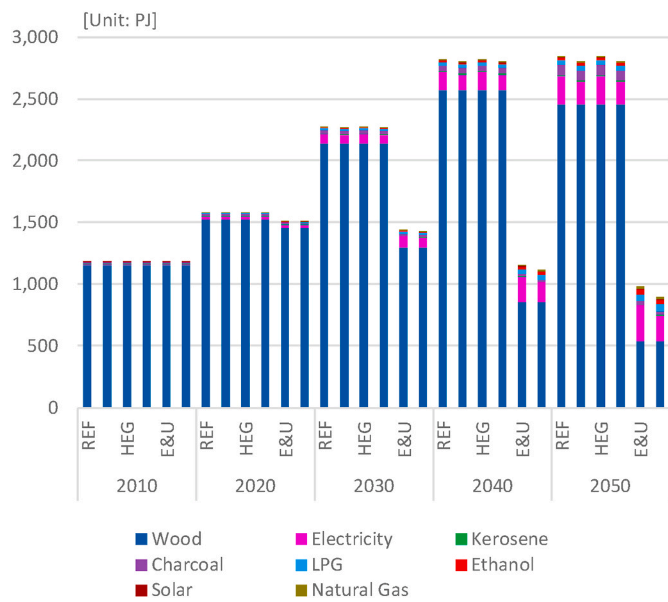

Fig. 8. Household fuel consumption under all scenarios.

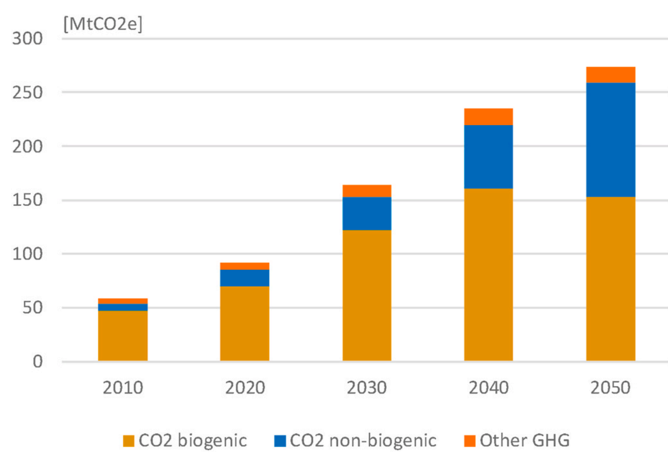

Fig. 9. Total GHG emission under BAU scenario.

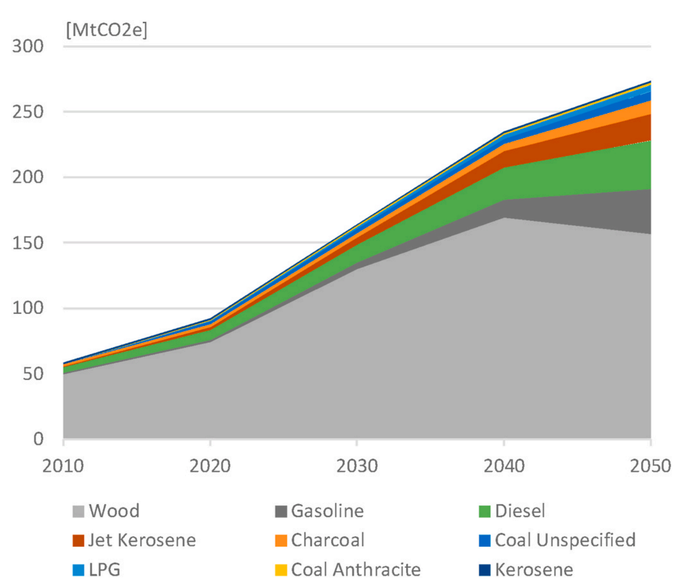

Fig. 10. Total GHG emission by fuel under BAU scenario.

the potential to become "carbon neutral" only over very long-time scales but not in the short term.

In addition, there are also other small non-CO_2 GHG emissions like carbon monoxide, methane, non-methane organic compounds, nitrogen oxides, nitrous oxide, etc. (see Fig. 9).

Biogenic carbon dioxide emissions are expected to further increase from 122 $MtCO_2e$ in 2030 to 160 $MtCO_2e$ in 2040 and then slowly decrease. On the other hand, non-biogenic carbon dioxide emissions keep on increasing by more than a fourfold from 30 $MtCO_2e$ in 2030 to 106 $MtCO_2e$ in 2050. This shows that the transport sector heavily relies on fossil-fuel and could be a potential target to reduce CO_2 emission in the long-run.

There is a large difference of total GHG emissions between the different scenarios. As can be seen from Fig. 11, in the BAU & IEE-1 and HEG & IEE-2 scenarios, emissions are much higher than in the E&U & IEE-3 scenarios. The BAU scenario's total GHG emissions in 2050 are estimated to reach 274 $MtCO_2e$ and the HEG scenario releases about 295 $MtCO_2e$. On the other hand, the E&U & IEE-3 scenario emissions are only projected to be 111 $MtCO_2e$. This difference is mainly due to the policy-driven shift from biomass-based household appliances to clean biofuel and electric-based appliances. Fig. 11 also shows that there is no impact from policy in the policy-driven scenarios on the GHG emission since the policies are implemented on the electricity sector with no emissions.

6. Conclusion and policy implications

In this study, six scenarios are assessed to represent the alternative development pathways of Ethiopia's energy future from 2018 to 2050. The comparative analysis between evaluated scenarios shows that the energy demand will significantly increase for the BAU and the HEG scenarios mainly due to population growth and economic development but much more moderately for the E&U scenario due to faster electrification and urbanization resulting in lower biomass-based consumption. The electricity demand increases strongly for BAU but even more for HEG and E&U. This is due to high rate of urbanization, electrification and economic development. The scenario independent strong increase shows the need for new capacity additions. The result of the policy scenarios (IEE-1, IEE-2 and IEE-3) shows that while the application of energy efficiency policies and measures would only have a minor impact on the energy demand, their impact on the electricity demand is large, and that the application of such policies is a very important measure to combat supply-demand mismatch causing power shortages and blackouts. Further, it is interesting to note that the electricity demand development is very similar for the three policy scenarios both with regard to overall demand and sector-specific demands. The electricity

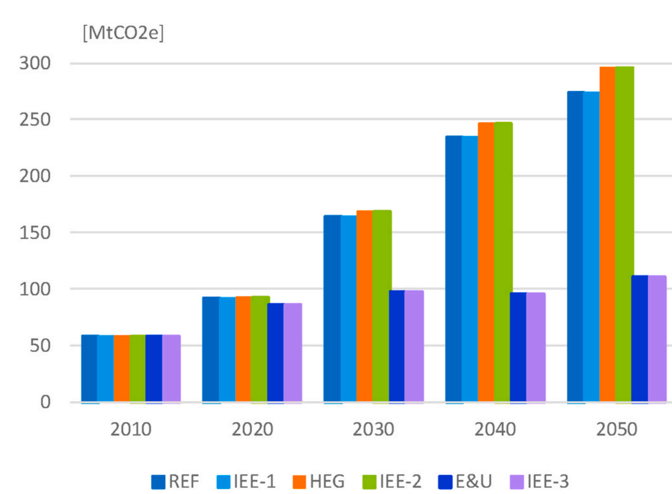

Fig. 11. Total GHG emission for all scenarios.

demand is increasing strongly in all sectors.

In all the years, the household sector accounts for the highest share of the energy demand followed by the transport sector. It is seen that it is possible to potentially reduce the household sector consumption by rapidly shifting from biomass-based energy consumption to clean-fuel (biofuel and electric)-based consumption. However, such technology transitions are not automatic and require state intervention through appropriate policy-development. In this regard, the current very low electricity access rate in rural areas should improve in the near future. Moreover, better service reliability and good power quality is also an important requirement to minimize the use of biomass and fossil fuel-based backup solutions during interruptions and power outages. This in turn requires good power system planning.

The energy demand evolution under the BAU and HEG scenarios show that the household sector and other sectors will heavily rely on biomass and fossil-fuels that lead to significant CO_2 emission. On the other hand, the E&U and IEE-3 scenarios result in a much lower energy demand resulting in significant reduction of CO_2 emissions. This implies that it is possible for Ethiopia to potentially reduce its biomass dependency and CO_2 emission by setting the right policies and implementing various strategies. It is also shown that electricity efficiency improvements are crucial for controlling the evolution of the electricity demand through proper energy policies. Considerable energy can be saved by implementing policy-driven efficiency measures through technology improvement, DSM activities, industrial energy audit and network loss reduction. The Ethiopian government has already started to explore several measures including standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. To ensure the effectiveness of these programs in achieving electricity efficiency improvements, the government should focus on long-term policies and strategies that can have significant impact on the future electricity sector.

Authorship statement

Dawit Habtu Gebremeskel: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing- Original Draft, Visualization. Erik O. Ahlgren: Supervision, Writing – review & editing. Getachew Bekele Beyene: Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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